Engineering 19 (2022) 7–10

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

News & Highlights

Construction Industry Innovation Takes Aim at Reducing Carbon Emissions

Mitch Leslie

Senior Technology Writer

With only 18 floors, Mjøstårnet, a ruddy blonde building in Brummundal, Norway (Fig. 1), is dwarfed by modern skyscrapers. It is not even the tallest building in Norway. But the structure, which includes offices, apartments, and a hotel, stands out for another reason—it is built almost entirely of wood [1]. Instead of the usual steel or concrete, the building's beams, columns, and trusses are made from glulam, produced by gluing pieces of wood together with the grain in parallel [2]. The lower floors, walls, stairs, and elevator shafts are also constructed of wood [3]. Only the floors of the upper stories, which contain the apartments, are concrete to increase stability and improve acoustics [4].

For three years after its completion in 2019, the 85.4 m Mjøstårnet was the world's tallest timber building, but the Ascent MKE tower in Milwaukee, WI, USA, which opened in mid-2022, is just over 1 m taller [5]. More than 1300 other so-called mass timber buildings, which substitute engineered wood products such as glulam for steel and concrete, are currently under construction in the United States alone [6].

Building skyscrapers out of wood is just one novel approach for reducing the enormous amount of greenhouse gases generated by construction. Other strategies that are under development or already being implemented include replacing coal with hydrogen in steel plants and redesigning concrete slabs to use less material. Addressing the problem now is critical, said Kate Simonen, a professor of architecture at the University of Washington in Seattle, WA, USA, because construction will surge in the near future to accommodate human population growth and urbanization and to provide better housing and infrastructure in developing countries. "Globally, the amount of building that needs to take place in the next few decades is phenomenal," she said.

What experts call the construction value chain—which includes the mining and processing of raw materials, along with the construction, maintenance, and operation of buildings—is responsible for about 25% of the world's total greenhouse gas emissions, according to the New York City-based consulting firm McKinsey & Company [7]. The diesel-powered excavators and bulldozers lumbering around construction sites account for a share, as do the factories that make glass and interior materials such as carpet [8–10]. But steel and concrete are the biggest climate culprits [11]. Manufacturing steel for construction generates about 3.5% of global greenhouse gas emissions, and production of concrete pumps out about 4.5% [7,12].

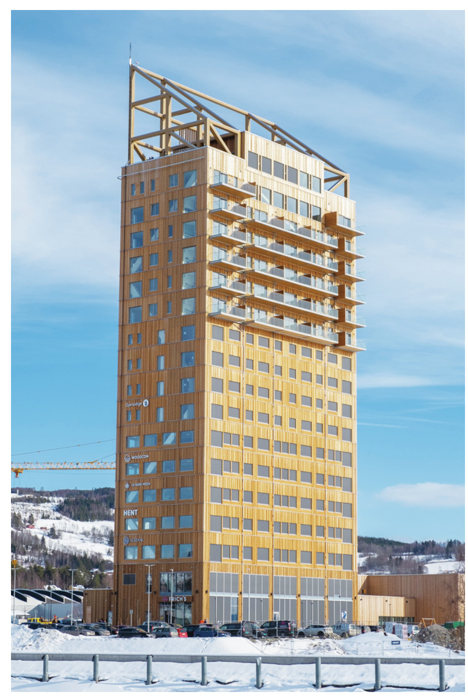

Fig. 1. The 18-story Mjøstårnet building in Norway gets most of its strength from engineered wood, which forms all its beams, columns, and trusses. The wooden beams that support its floors can be up to 720 mm thick, and the four columns at the corners of the building are 1425 mm thick. Credit: Wikimedia Commons (CC BY-SA 4.0).

Engineered wood could help curb those emissions by taking some of the load off concrete and steel. Mass timber can be comparable in strength to these materials [6] and can lead to dramatic carbon reductions. In a study published in 2019, Simonen and colleagues calculated that constructing an eight-story building from cross-laminated timber, an engineered wood material like glulam, would produce almost 27% less carbon than if the building were

https://doi.org/10.1016/j.eng.2022.10.001

made from concrete [13]. Regulations are evolving to allow modest-sized mass timber structures. The International Building Code, a standard for much of the world, now sanctions wooden structures of up to 18 stories [14]. But builders are looking to go even higher—a 70-story wooden tower in Tokyo and an 80-story skyscraper in London are on the drawing board [6].

Despite its appeal, mass timber still accounts for a relatively small share of new construction [1]. Two of its drawbacks are high costs, which still exceed those for traditional materials, and the vast amounts of wood required. Constructing the Mjøstårnet and a smaller nearby structure took 18 000 trees [1]. Simonen cautioned that mass timber buildings only lower carbon emissions if they are built from wood grown in sustainably managed forests. Increasing the supply of this wood will take time, but "emerging methods" for using fast-growing plant material such as bamboo and straw in structures "are promising," she said [15,16].

Even if there is an engineered wood building boom in the next few decades, the world will still need concrete and steel for construction. But changing how these materials are made and used could help slash their greenhouse gas production, experts say. The concrete industry has committed to reducing its carbon emissions, which have tripled since 1992 [17]. The Global Cement and Concrete Association, the world's largest organization of cement manufacturers, has promised to be carbon neutral by 2050 and has laid out a plan to reach that goal [18]. Governments are also taking—or at least promising—action. In 2021, California, which uses the second most concrete of any US state, passed a law that requires cement makers to reach net zero for carbon emissions by 2045 [19]. Many of the world's biggest economies, including the United States, the European Union, and Japan, have pledged to be carbon neutral by 2050, and China, which makes 55% of the world's concrete, aims to reach that goal by 2060 [20,21].

Still, decarbonizing concrete manufacturing remains a huge challenge [22]. Most of concrete's climate impact stems from production of its key ingredient, cement. An early step in making the most-used type of cement involves cooking limestone—which is largely calcium carbonate—at 850–900 °C to produce lime and CO_2 [11,23]. This step alone is responsible for 60% of a cement plant's CO_2 emissions and energy use [23]. However, the next step, in which lime is mixed with sand and clay and baked in a kiln, also requires significant amounts of energy to raise the temperature to more than 1400 °C [11,23]. The product of this stage, known as clinker, is further processed to produce cement, which is then combined with water, sand, and gravel to yield concrete [11].

There is no shortage of ideas for reducing carbon emissions from the concrete-making process. Using less cement or clinker is one strategy. Materials such as fly ash from coal-fueled power plants are already added to cement so that less clinker is required. To further reduce the amount necessary, manufacturers could include more of these substitutes and mix in a broader range of materials, such as artificial fibers [11]. And alternatives such as calcined clay and limestone can fill in for cement. Several US states now permit the use of concrete in which ground limestone replaces 5%–15% of the cement [24]. Other approaches target the biggest source of CO_2, limestone cooking [25]. Instead of limestone, cement from the Oakland, CA, USA-based startup Brimstone uses calcium silicate that does not yield CO_2—the company even claims its cement absorbs CO_2 from the air [26].

Re-engineering structures could also reduce greenhouse gas emissions. For example, Paul Shepherd, a reader in architecture and civil engineering at the University of Bath in the United Kingdom, and colleagues have revised the humble concrete floor slab that is a structural component of most buildings. The prototype he and his colleagues have created (Fig. 2) "uses concrete the way it wants to be used," said Shepherd. "Concrete works great in compression but not in tension," he said. The bowed shape of their slab permits the concrete to resist compression and lessens the amount of tension it is under, thus allowing the slab to be thinner. A flat deck is added to create a level floor, and pipes, conduits, and wiring can pass in the space between the deck and slab, so the building's height is unaffected. The team's approach also abandons the wasteful pouring process, in which concrete is slopped into forms. Instead, a robot makes the slab by spraying layer upon layer of concrete impregnated with a reinforcing material made from glass fiber [27]. These changes reduced the amount of concrete required to build the slab by 75% and cut its carbon footprint by 60%, Shepherd said.

Fig. 2. Designed by Paul Shepherd of the University of Bath in the United Kingdom and colleagues, this curved concrete slab generates 60% less greenhouse gas emissions than a traditional slab. Shepherd is standing atop a floor resting on the slab. Credit: University of Bath, with permission.

Although approaches like these might diminish the concrete sector's carbon emissions, the industry and some experts argue that reaching net zero will also require carbon capture, utilization, and storage (CCUS) [11,12,18]. This technology withdraws carbon from a plant's exhaust and then sequesters it, or even diverts it to make products such as plastics [28]. One storage site could be concrete itself—some companies are testing whether they can inject captured carbon into cement to help it harden [25]. The cement industry has started using carbon capture on a small scale. A pilot plant opened in China in 2019 [29], and the German company Heidelberg Cement, the world's second largest cement maker, has two such facilities in the works [30]. However, critics charge that relying on carbon capture is risky because the technology has a poor record [31]. For example, a recent review of 13 prominent carbon capture projects found that two failed and most of the rest removed much less carbon than predicted [32]. Carbon capture also remains expensive. According to one estimate, implementing CCUS for the concrete industry would increase the cost of manufacturing cement by 25% [11].

When it comes to decarbonization, steel poses many of the same problems as concrete [22]. Manufacturing both materials is energy-intensive, depends on fossil fuels, and involves processes that generate large amounts of CO_2. But a variety of innovations could help reduce steel's carbon footprint. Jinsoo Kim, an associate professor of earth resources and environmental engineering at Hanyang University in the Republic of Korea, and colleagues have identified 86 interventions that could cut steel's carbon emissions, all of which are available now or may soon be practicable [33].

In the most common procedure for making steel, the step that emits the most carbon occurs in a blast furnace (Fig. 3), as a mixture of oxygen-rich iron ore and a type of coal known as coking coal can reach more than 2000 °C [11,34]. CO from the coking coal swipes oxygen atoms from the iron ore, yielding CO_2 and molten pig iron—a transformation known as reduction [34]. The pig iron then undergoes further processing to produce steel—and more CO_2 [35].

About 5% of the world's steel plants use hydrogen and CO derived from fossil fuels, rather than coking coal, to reduce iron ore [11,34]. The directly reduced iron formed in this way becomes

Fig. 3. Amid this shower of sparks from a steel plant's blast furnace, iron ore and coking coal are reacting to produce pig iron and CO_2. In the most common steelmaking process, this step yields the most CO_2. Credit: Třinecké železárny, with permission.

steel in an electric arc furnace [34]. This process generates up to 40% less CO_2 [34].

However, switching to "green" hydrogen produced without fossil fuels could cut emissions further. At a pilot plant for the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project in Sweden, for instance, wind turbines generate electricity to produce hydrogen gas through electrolysis of water [34]. The hydrogen then feeds into a furnace and reduces iron ore, yielding water as a byproduct [31,35]. This approach cuts the CO_2 emissions from the steelmaking process by 97% [11]. The HYBRIT plant completed its first batch of steel in 2021 [35], and similar pilot plants are operating in other countries [36].

Availability of hydrogen remains an obstacle for this approach, said Richard Curry, program manager for the Strategic University Steel Technology and Innovation Network (SUSTAIN), a consortium of industry and academic researchers based at the University of Swansea in the United Kingdom. Relative to other fuel sources, "the supply of hydrogen is nothing at the moment," he said. And producing more will demand large amounts of energy [37]. If all existing steel plants switched to green hydrogen, supplying the gas would require twice the world's current output of renewable energy and nuclear power, researchers have calculated [37]. Moreover, said Curry, the reaction between hydrogen and iron ore requires additional energy, meaning that producing steel with this approach "is still not commercial."

Two other routes for curbing the steel industry's greenhouse gas output are carbon capture and increased recycling of scrap iron. But neither is ready to make a dramatic difference, said Curry. He noted that carbon capture methods typically involve amine molecules that are destroyed by the wide swings of temperature and pressure in steel plants, reducing the technology's effectiveness. Researchers, including SUSTAIN Steel members, are testing alternatives for trapping carbon, but these approaches are still under development, Curry said. And though about 25% of steel is currently made from recycled scrap iron, the supply of reusable iron is often contaminated with materials such as other metals and plastics. To boost the amount of scrap recycled, the industry needs more efficient sorting and analysis methods, he said.

The expense of producing "green" steel is likely the largest barrier to decarbonizing the industry, said Kim. "The global iron and steel market is highly competitive, and thus production cost matters." Reducing steel's climate impact will require an international effort, he said. "Without cooperation, the decarbonization of the industry cannot be done."

Simonen adds that cutting construction's carbon emissions will require solutions that address not just steel and concrete, but all the industry's sources of greenhouse gases—and that dovetail with efforts to reduce the climate impact of other sectors, including electricity generation. She emphasized that although technological advances are important, cultural change is also necessary. Today, for instance, planners often prefer to demolish and replace old buildings. But restoring and adapting old structures instead could produce substantial carbon savings, she said. To meet climate change and sustainability goals, "We have to rethink where we build, how we build, and when we build."

References

[1] Mead R. Transforming trees into skyscrapers [Internet]. New York City: The New Yorker; 2022 Apr 18 [cited 2022 Aug 25]. Available from: https://www.newyorker.com/magazine/2022/04/25/transforming-trees-into-skyscrapers.
[2] Tumari K. Mjøstårnet: the tallest timber building in the world [Internet]. Vadodara: The Constructor; [cited 2022 Aug 25]. Available from: https://theconstructor.org/building/buildings/mjostarnet-building-set-new-world-record/58592/.
[3] Mjosa Tower (Mjøstårnet) [Internet]. London: Design Build Network; 2019 May 17 [cited 2022 Aug 25]. Available from: https://www.designbuild-network.com/projects/mjosa-tower-mjostarnet.
[4] Kingson JA. The race to build wooden skyscrapers [Internet]. Arlington: Axios; 2022 Apr 26 [cited 2022 Aug 25]. Available from: https://www.axios.com/2022/04/26/wooden-skyscrapers-mass-timber.
[5] Willlcoxon M. The tallest mass timber building in the world is opening in downtown Milwaukee. It's healthier for the planet. And you [Internet]. Milwaukee: Milwaukee Journal Sentinel; 2022 Jun 29 [cited 2022 Aug 25]. Available from: https://www.jsonline.com/story/news/2022/06/29/milwaukee-newest-mass-timber-structure-ascent-opens-summer-sustainable-architecture/7653606001/.
[6] Niiler E. Wooden skyscrapers are on the rise [Internet]. New York City: Wall Street Journal; 2022 Apr 11 [cited 2022 Sep 8]. Available from: https://www.wsj.com/articles/wooden-skyscrapers-are-on-the-rise-11649693924.
[7] Call for action: seizing the decarbonization opportunity in construction [Internet]. New York City: McKinsey & Company; 2021 Jul 14 [cited 2022 Aug 25]. Available from: https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/call-for-action-seizing-the-decarbonization-opportunity-in-construction.
[8] Romeo N. How Oslo learned to fight climate change [Internet]. New York City: The New Yorker; 2022 May 4 [cited 2022 Aug 25]. Available from: https://www.newyorker.com/news/annals-of-a-warming-planet/how-oslo-learned-to-fight-climate-change.
[9] Smil V. The stunning carbon footprint of plate glass [Internet]. New York City: IEEE Spectrum; 2022 Mar 30 [cited 2022 Aug 25]. Available from: https://spectrum.ieee.org/float-glass.
[10] Gertner J. Has the carbontech revolution begun? [Internet]. New York City: New York Times; 2021 Jun 27 [cited 2022 Aug 25]. Available from: https://www.nytimes.com/2021/06/23/magazine/interface-carpet-carbon.html.
[11] Fennell P, Driver J, Bataille C, Davis SJ. Cement and steel—nine steps to net zero. Nature 2022;603:574–7.
[12] Hundertmark T, Reiter S, Schulze P. Green growth avenues in the cement ecosystem [Internet]. New York City: McKinsey & Company; 2021 Dec 16 [cited 2022 Aug 25]. Available from: https://www.mckinsey.com/industries/chemicals/our-insights/green-growth-avenues-in-the-cement-ecosystem.
[13] Pierobon F, Huang M, Simonen K, Ganguly I. Environmental benefits of using hybrid CLT structure in midrise nonresidential construction: an LCA based comparative case study in the US pacific northwest. J Build Eng 2019;26:100862.
[14] Kleeman A. Use of cross-laminated timber may rise in the US [Internet]. London: Reuters; 2022 Aug 25 [cited 2022 Sep 8]. Available from: https://www.reuters.com/legal/legalindustry/use-cross-laminated-timber-may-rise-us-2022-08-25/.
[15] Cairns R. Bamboo has been used for thousands of years in Asia. Now, it could help solve construction's sustainability problem [Internet]. Atlanta: CNN; [updated 2021 Nov 22; cited 2022 Sep 13]. Available from: https://www.cnn.com/style/article/bamboo-sustainable-building-philippines-bali-hnk-spc-intl/index.html.
[16] Miles P. Straw-inspiring: houses made of the humble bale [Internet]. London: Financial Times; 2021 Dec 3 [cited 2022 Sep 13]. Available from: https://www.ft.com/content/a42d0a24-2543-445e-83f1-8227d0110756.
[17] Borenstein S. Cement carbon dioxide emissions quietly double in 20 years [Internet]. New York City: Associated Press; 2022 Jun 22 [cited 2022 Aug 25]. Available from: https://apnews.com/article/climate-science-china-pollution-3d97642acbb07fca7540edca38448266.
[18] Concrete future [Internet]. London: Global Cement and Concrete Association; [cited 2022 Aug 25]. Available from: https://gccassociation.org/concretefuture/.
[19] Mulkern AC. Nut shells fuel cement kilns as Calif. imposes climate law [Internet]. Washington, DC: E&E News; 2021 Oct 28 [cited 2022 Aug 25]. Available from: https://www.eenews.net/articles/nut-shells-fuel-cement-kilns-as-calif-imposes-climate-law/.
[20] Concrete needs to lose its colossal carbon footprint. Nature 2021; 597:593–4.

[21] Normile D. Can China, the world's biggest coal consumer, become carbon neutral by 2060? [Internet]. Washington, DC: Science; 2020 Sep 29 [cited 2022 Aug 25]. Available from: https://www.science.org/content/article/can-china-worlds-bigger-coal-consumer-become-carbon-neutral-2060.

[22] Dunn K. From concrete to steel, how construction makes up the "last mile" of decarbonization [Internet]. New York City: Fortune; 2021 Feb 16 [cited 2022 Aug 25]. Available from: https://fortune.com/2021/02/16/concrete-steel-construction-design-climate/.

[23] Fennell PS, Davis SJ, Mohammed A. Decarbonizing cement production. Joule 2021;5(6):1305–11.

[24] Srubar W. Concrete is more polluting than flying. Here are 4 innovative ways to clean it up [Internet]. New York City: Fast Company; 2022 Sep 10 [cited 2022 Sep 17]. Available from: https://www.fastcompany.com/90786922/concrete-more-polluting-than-flying-4-ways-to-decarbonize-cement-industry.

[25] How cement may yet help slow global warming [Internet]. London: The Economist; 2021 Nov 4 [cited 2022 Aug 25]. Available from: https://www.economist.com/science-and-technology/how-cement-may-yet-help-slow-global-warming/21806083.

[26] Clifford C. These scientists bonded over toilet tech. Now they're working on carbon-free cement [Internet]. New York City: CNBC; 2022 Apr 28 [cited 2022 Aug 25]. Available from: https://www.cnbc.com/2022/04/28/carbon-free-cement-breakthrough-dcvc-put-55-million-into-brimstone.html.

[27] Changing floor shape could cut concrete usage by 75 percent [Internet]. Stevenage: E&T; 2022 Feb 21 [cited 2022 Aug 25]. Available from: https://eandt.theiet.org/content/articles/2022/02/changing-floor-shape-could-cut-concrete-usage-by-75-per-cent/.

[28] Leslie Davis A. How to make recyclable plastics out of CO_2 to slow climate change [Internet]. Washington, DC: Science News; 2022 Sep 9 [cited 2022 Sep 14]. Available from: https://www.sciencenews.org/article/plastic-carbon-dioxide-capture-recycling-climate-change.

[29] Stanway D. Concrete steps? For China cement giants, monster carbon footprint smothers climate goals [Internet]. London: Reuters; 2019 Sep 12 [cited 2022 Aug 25]. Available from: https://www.reuters.com/article/us-climate-change-china-cement/concrete-steps-for-china-cement-giants-monster-carbon-footprint-smothers-climate-goals-idUSKCN1VX0QQ.

[30] Dempsey H. HeidelbergCement aims to tackle emissions with new carbon-neutral cement plant [Internet]. London: Financial Times; 2021 Jun 2 [cited 2022 Aug 25]. Available from: https://www.ft.com/content/74a49a0c-bfe9-4f0b-a8a0-7e607d91d387.

[31] De La Garza A. The inflation reduction act includes a bonanza for the carbon capture industry [Internet]. New York City: Time; 2022 Aug 11 [cited 2022 Aug 25]. Available from: https://time.com/6205570/inflation-reduction-act-carbon-capture/.

[32] Vaughan A. Most major carbon capture and storage projects haven't met targets [Internet]. London: New Scientist; 2022 Sep 1 [cited 2022 Sep 8]. Available from: https://www.newscientist.com/article/2336018-most-major-carbon-capture-and-storage-projects-havent-met-targets/.

[33] Kim J, Sovacool BK, Bazilian M, Griffiths S, Lee J, Yang M, et al. Decarbonizing the iron and steel industry: a systematic review of sociotechnical systems, technological innovations, and policy options. Energy Res Soc Sci 2022;89:102565.

[34] Peplow M. Can industry decarbonize steelmaking? [Internet]. Washington, DC: Chemical & Engineering News; 2021 Jun 13 [cited 2022 Aug 25]. Available from: https://cen.acs.org/environment/green-chemistry/steel-hydrogen-low-co2-startups/99/i22.

[35] De La Garza A. The world's steel comes at a steep climate cost. A Swedish company is trying to change that [Internet]. New York City: Time; 2022 Apr 28 [cited 2022 Aug 25]. Available from: https://time.com/6171369/ssab-sweden-green-steel/.

[36] Pfeifer S. ArcelorMittal successfully tests use of green hydrogen at Canadian plant [Internet]. London: Financial Times; 2022 May 1 [cited 2022 Aug 25]. Available from: https://www.ft.com/content/cce5439a-3c26-4331-9455-094edb638df4.

[37] Hutson M. The promise of carbon-neutral steel [Internet]. New York City: The New Yorker; 2021 Sep 18 [cited 2022 Aug 25]. Available from: https://www.newyorker.com/news/annals-of-a-warming-planet/the-promise-of-carbon-neutral-steel.